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Analog Breakthrough Detection using laser-Induced, Thermal Diffusion Shock Waves

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Abstract

The efficiency of a jet engine is improved by increasing the temperature in the engine combustion components. Combustion chamber temperatures have increased up to 1600° C over the past decade. Therefore, jet engine combustion components must deal with high temperatures. Free-air-flow cooling holes are critical for cooling the components. But the process of drilling cooling holes has numerous problems, and back wall strike is the major problem that must be solved. This thesis presents innovative approaches to designing controllers for the laser percussion drilling process to determine the exact moment of breakthrough to eliminate back wall strike, which damages the adjacent surface of jet-engine turbine components. LabVIEW was used to establish control principles, and approximately 20 Gigabytes of data were collected at the Connecticut Center for Advanced Technology (CCAT) in 2007 and 2008 using the National Instruments PXI-4462 Dynamic Signal Acquisition Board and the PXI-5922 Flexible-Resolution Digitizer. Dedicated controllers were built based on the data recorded at CCAT, and the test results proved that these approaches were promising.

INTRODUCTION

A. Statement of the Problem

The laser percussion drilling process at the Connecticut Center for Advanced Technology (CCAT) is shown in Figure 1. The laser beam was generated by the neodymium-doped yttrium aluminum garnet (Nd: YAG) laser of the Convergent Prima P-50 laser drilling machine at CCAT. The laser beam passed through the center of the copper nozzle and impinged upon the surface of a Waspalloy steel plate sample. The angle between the laser and sample is 20 degrees, which is the standard for cooling hole drilling for jet engine turbine blades. After a few percussion-drilling operations, the laser beam started penetrating the sample and making a small diameter hole on the sample surface; this process is known as "partial breakthrough". At the next laser shot, the laser beam completely penetrated the sample; this process is known as "full breakthrough."

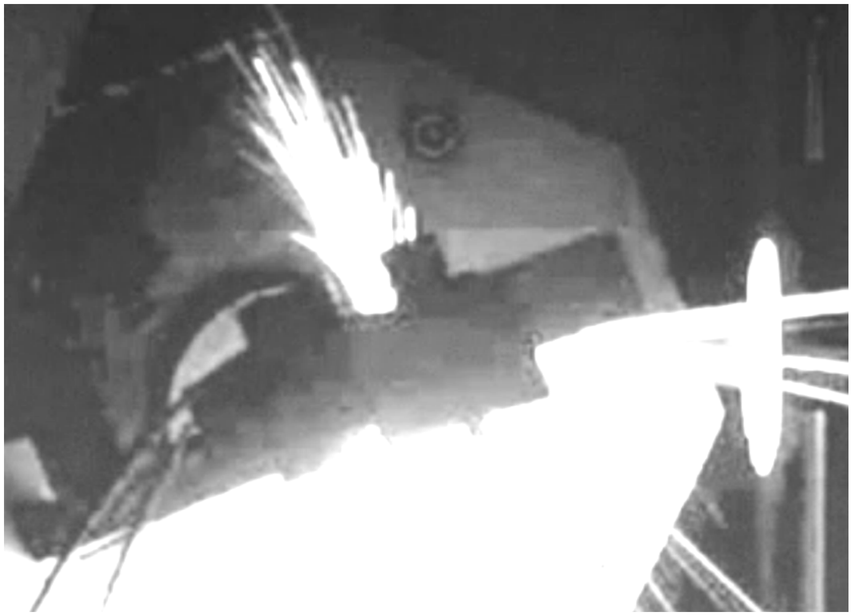


Figure 1. Laser Percussion Drilling Process at Connecticut Center for Advanced Technology

But subsequent laser shots continuously drilled the adjacent sample surface after full breakthrough in the laser percussion drilling process of actual jet engine turbine blades.This unavoidable process is known as “back wall strike.” In order to diminish the effect of back wall strike, Loctite Hysol 7901 polyamide hot melt might be injected in cavities of jet engine turbine blades. But the adjacent sample surface might receive serious surface damage despite the existence of the hot melt. In order to solve this problem, the exact moment of full breakthrough must be detected by the sensor, and the controller must turn off the laser immediately after the exact moment of full breakthrough. Many approaches have been developed to minimize the effect of back wall strike. Full breakthrough can be detected by frequency changes of the drilling sound signatures using the FFT. Also, it can be detected by spectrum changes of the percussion-drilling arc. It can also be detected by a video camera that is mounted to view the area being drilled through a path coaxial with the drilling laser beam [1]. In this project, the PCB-106B pressure sensor was used to measure laser-induced thermal diffusion shock waves to detect the moment of full breakthrough. The output of the PCB-106B pressure sensor was processed to show clear evidence of the moment of full breakthrough when the laser beam completely penetrated the sample.

B. Hypothesis

Temperature Changes and Laser-Induced Thermal Diffusion Shock Waves

Temperature changes are directly related to the progress of the laser percussion drilling process. The temperature of the sample dramatically increases when the laser impinges upon the sample surface, and it dramatically decreases right after full breakthrough. In order to prove the relationship between the output of the pressure sensor and the temperature conditions of the sample, the following experiments were conducted in a laboratory. A cigar lighter was ignited, and the flame was passed in front of the PCB106B52 pressure sensor as shown in Figure 2. Then it was moved away from the sensor and extinguished. The results are shown in Figure 3, and summarized as follows:

1. When the flame was passed in front of the PCB106B52 pressure sensor, the output of the second derivative was positive.
2. When the flame was moved away from the PCB106B52 pressure sensor, the output of the second derivative was negative.

Therefore, it was considered that it might be possible to determine the moment of full breakthrough by measuring the output of the pressure sensor that receives the thermal diffusion shock waves from the heat source. The major difference between this lab experiment and the laser percussion drilling experiment at CCAT was the magnitude of the thermal diffusion shock waves. The magnitude was approximately 3.5kPa in the lab experiment and approximately 81kPa in the percussion laser drilling process at CCAT. The PCB-106B52 pressure sensor was used in this lab experiment instead of the PCB106B pressure sensor because the PCB-106B52 pressure sensor provides the highest sensitivity and the lowest resolution in the PCB-106 series pressure sensors [2].

Figure 2. PCB106B52 Sensor Setup

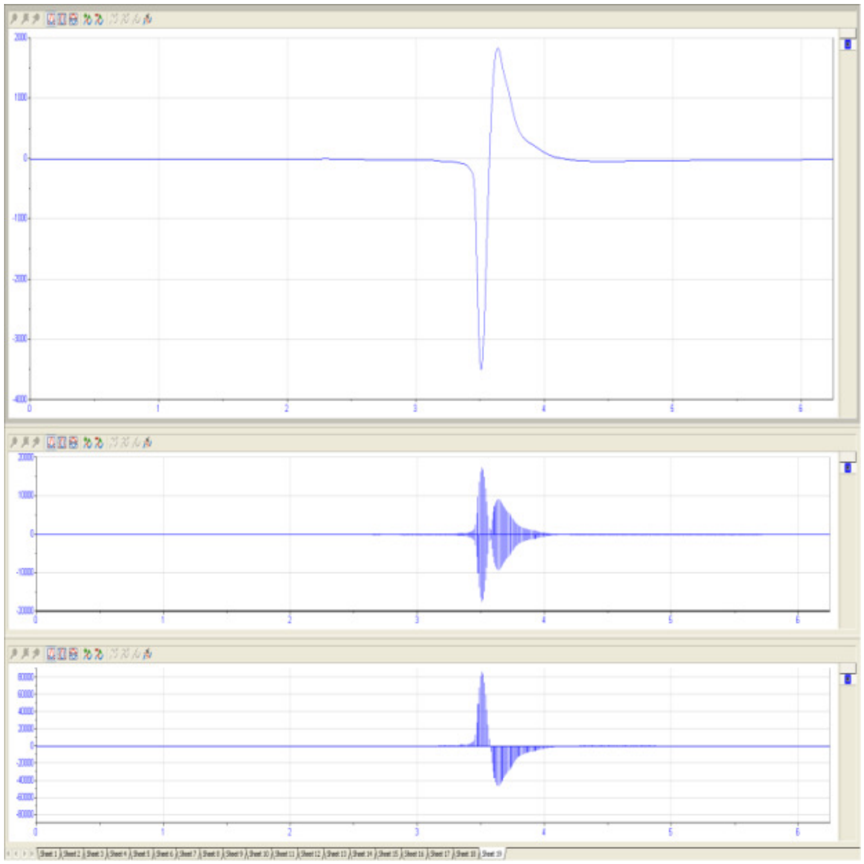


Figure 3. PCB106B 52 Pressure Sensor Output (top)
First Derivative (middle) and Second Derivative (bottom)
XAxis: Time in Second Y Axis: Sensor Output

C. Partial Breakthrough and Full Breakthrough

In the percussion drilling process, the laser beam penetrates the sample after drilling repeatedly and makes a small diameter hole. This condition is called partial breakthrough. At the following laser shot, the laser beam completely penetrates the sample and makes a big diameter hole. This condition is called full breakthrough. These conditions are shown in Figure 4. The diameters of these holes can be estimated using the diameter of calibration dots.

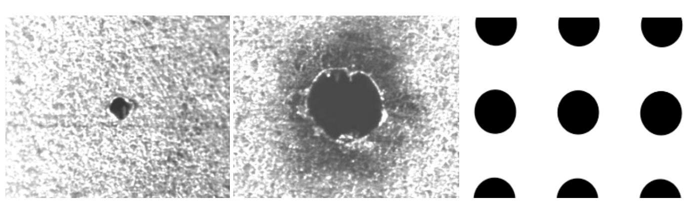
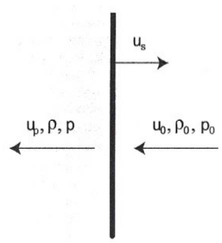


Figure 4. Partial Breakthrough, Full Breakthrough and Calibration Dots (0.25mmØ)

D. Laser-Induced Thermal Diffusion Shock Waves

The effects of laser induced thermal diffusion shock waves have been investigated and the fundamental equations were established by Sorasak Danworaphong, Gerald J. Diebold and Walter Craig in the book "Laser Induced Thermal Diffusion Shock Waves." When a neodymium-doped yttrium aluminum garnet (Nd: YAG) laser induces a thermal diffusion shock wave, the thermodynamic properties−speed U, density ρ, and pressure P−are dramatically different before the shock front and after the shock front. The figure of the shock front was extracted from the book and is shown in Figure 5 [3].



Source: Danworaphong, Sorasak, Gerald J. Diebold, and Walter Craig. *Laser Induced Thermal Diffusion Shock Waves.* Saarbrűcken, Germany: VDM Verlag Dr. Műller.
Figure 5. "Shock Front"

Thermal diffusion shock waves have several properties identical to fluid shock waves generated by supersonic flight [4]. The difference between thermal diffusion shock waves and fluid shock waves is as follows [4]:

1. Thermal diffusion shock waves depend on the existence of externally imposed temperature gradients, while fluid shock waves have no such requirement.
2. Thermal diffusion shock waves always appear as a pair of identical shock fronts that propagate in opposite directions.
3. The dissipating force is mass diffusion in thermal diffusion shock waves. But the speed of thermal diffusion shock waves will be eventually equal to zero even in the absence of mass diffusion. The dissipating force is viscous damping in fluid shock waves.

The thermal diffusion shock waves is governed by the following equation [4]:

$$\frac{\partial C(z,t)}{\partial \tau} = \alpha \frac{\partial}{\partial z}\{c(z, t)[1 - c(z, t)]\cos z\} + \frac{\partial^2 c(z, t)}{\partial z^2} \tag{1}$$

The significance of this equation is stated as follows:

1. The first term corresponds to thermal diffusion shock waves, and the second term corresponds to mass diffusion shock waves [4].
2. The sinusoidal function governs the first term, which represents thermal diffusion shock waves.

3. α is the thermal diffusion factor that is expressed as follows:

$$\alpha = \frac{D' T_0}{D} \quad (2)$$

D' is the thermal diffusion constant, D is the mass diffusion constant and To is the temperature. This α is the magnitude that governs the dominance of thermal diffusion shock waves over mass diffusion shock waves [4].

METODOLOGY

A. Setup

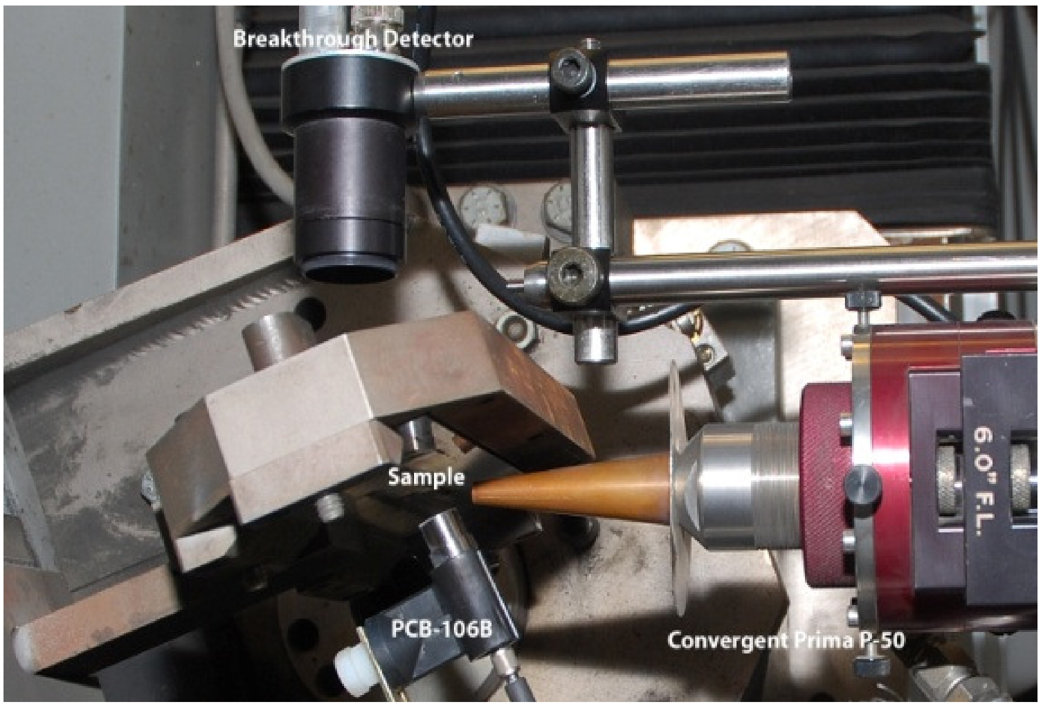


Figure 6. Laser Percussion Drilling Process Setup at Connecticut Center for Advanced Technology (CCAT), Breakthrough Detector (top) and Pressure Sensor (bottom)

The laser percussion drilling process setup at CCAT is shown in Figure 6. The laser beam was generated by the neodymium-doped yttrium aluminum garnet (Nd: YAG) laser of the Convergent Prima P-50 laser drilling machine at CCAT. The laser beam passed through the center of the copper nozzle and impinged upon the surface of a Waspalloy steel plate sample. The thermal diffusion shock waves were measured by the PCB-106B pressure sensor that was placed under the sample. Also, the penetrating laser power was measured by the breakthrough detector that was placed above the sample in order to confirm the moment of breakthrough that was detected by the PCB-106B pressure sensor. After full breakthrough, subsequent laser shots continuously drilled the adjacent sample surface, and this condition is the major problem in the laser percussion drilling process.

In order to eliminate the effect of back wall strike, the exact moment of full breakthrough must be detected by processing the output of the PCB-106B pressure sensor, and the controller must turn off the laser immediately after the exact moment of full breakthrough. There are two approaches to process the output of the PCB-106B pressure sensor, the analog approach and the digital approach, and the analog approach is focused in this paper.

APPARATUS

The National Instruments PXI-4462 Dynamic Signal Acquisition Device and the LabVIEW breakthrough detection program were used for the analog approach; the National Instruments PXI-4462 Dynamic Signal Acquisition Device is shown in Figure 7. This analog approach uses LabVIEW to differentiate the PCB106B pressure sensor output twice to get the second-derivative output that indicates temperature changes of the sample during the percussion laser drilling process. When the laser beam impinges upon the sample surface, the sample is in the heating stage, and the second-derivative value becomes positive. When the laser beam completely penetrates the sample after full breakthrough, the sample is in the cooling stage, and the second-derivative value becomes negative. When the absolute value of the negative second-derivative value exceeds a certain threshold value, it is considered full breakthrough, and the resulting signal shows a clear indication of full breakthrough to turn off the laser to prevent back wall strike.

Figure 7. National Instruments PXI-4462 Dynamic Signal Acquisition Device (the first module from the right)

The LabVIEW Breakthrough Detection program for the analog approach is shown in Figure 8 and consists of the following four major DAQmx blocks:

1. “Timing” configures the number of samples to acquire.
2. “Start Task” starts the task to begin the measurement.
3. “Read” reads the samples from the task.
4. “Clear Task” clears the task before cleaning.

This program differentiates the PCB-106B pressure sensor output twice, and the second derivative value is compared against a certain threshold value to detect the moment of full breakthrough. Also, it can record the following six signals in the TDMS format and save the data on the hard drive:

1. Output of the PCB-106B pressure sensor
2. First derivative of the output of the PCB-106B pressure sensor
3. Second derivative of the output of the PCB-106B pressure sensor
4. Output of breakthrough detection function
5. Laser power output from the Convergent Prima P-50 laser drilling machine
6. Output of the breakthrough detector

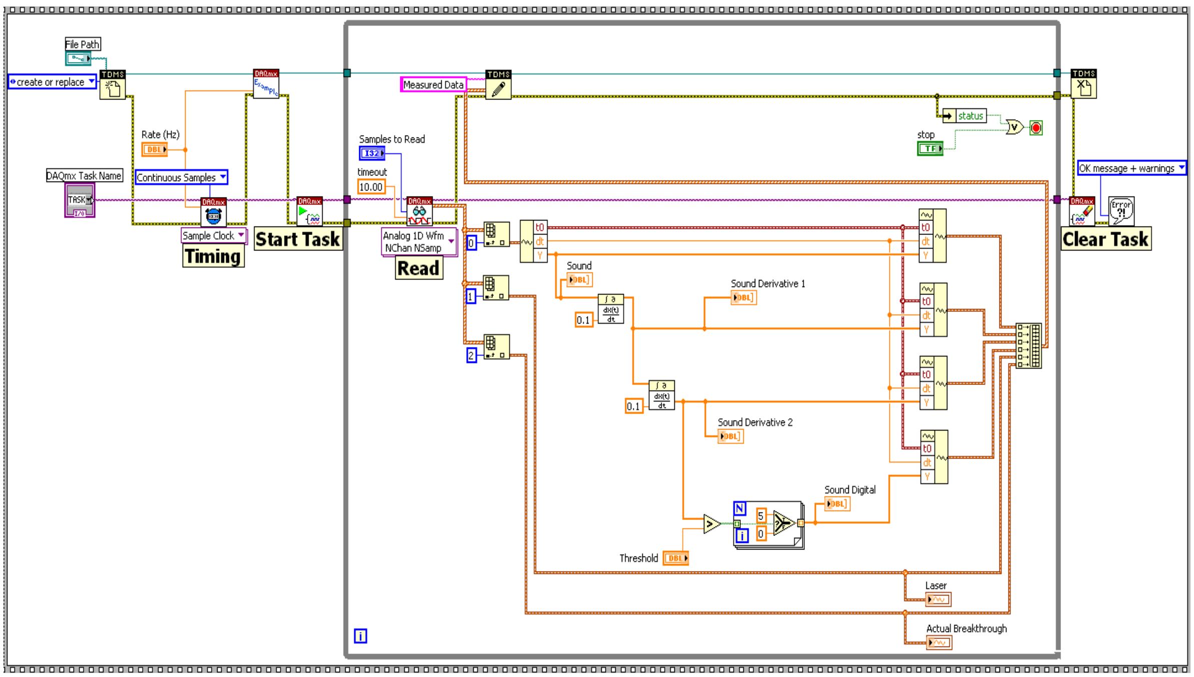


Figure 8. LabVIEW Breakthrough Detection Program for the Analog Approach

Results

A. Analog Approach Software Method

1. Pressure Sensor Output

The pressure sensor output and the breakthrough detector output are shown in Figure 9. The top blue line indicates the output of the PCB106B pressure sensor in Pa. The bottom red line indicates the output of the breakthrough detector in volts.

The horizontal line indicates the time in seconds. In this experiment, the data were collected using a sampling rate of 10kHz. So signals above 5kHz, which was the frequency range of the system gas noise, were all eliminated according to the Nyquist-Shannon sampling theorem [5]. Therefore, system gas noise from the copper nozzle was not observed. The total number of laser shots was seven, and the laser power was 13 joules per shot. Partial breakthrough occurred at the third shot, and full breakthrough occurred at the fourth shot. The pressure sensor output shows the distinct vertical line which represents the thermal contact between the laser beam and the sample. At full breakthrough on the fourth shot, the vertical line disappears. So the pressure sensor output directly indicates the moment of full breakthrough without any analysis tools.

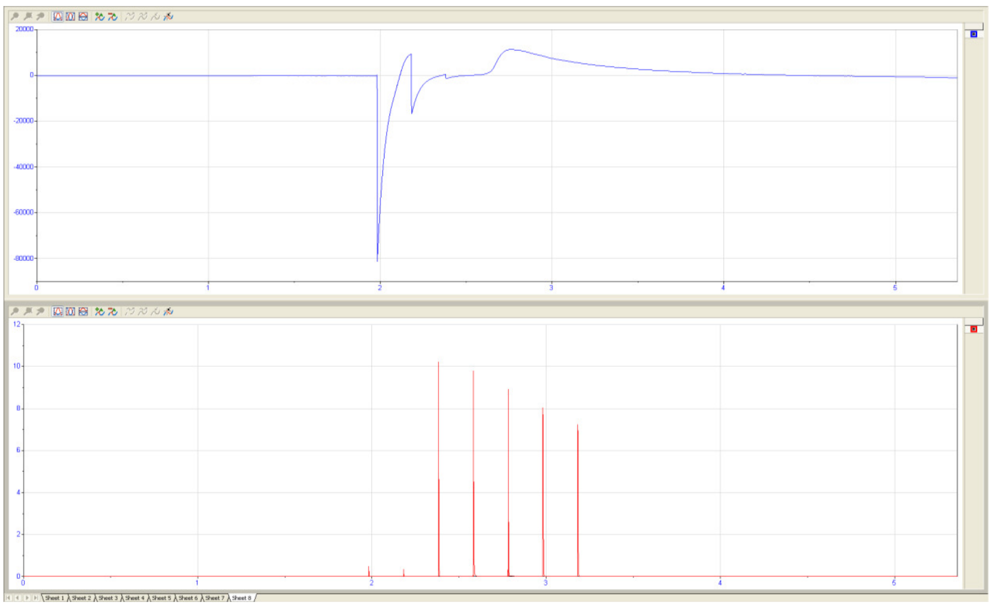


Figure 9. Pressure Sensor Output (top) and Breakthrough Detector Output (bottom)
X Axis: Time in Second Y Axis: Sensor Outputs in Pa (top) and Voltage (bottom)

The operations of the seven laser shots are summarized as follows:

1. The first laser shot impinged upon the sample surface and had the highest negative pressure.
2. The second laser shot had the second highest negative pressure.
3. The third laser shot partially penetrated the sample (partial breakthrough) and had the third highest negative pressure.
4. The fourth laser shot fully penetrated the sample, and the pressure sensor did not show any vertical response (full breakthrough).
5. The fifth laser shot cleaned up the existing hole, and the pressure sensor did not show any vertical response.
6. The sixth laser shot further cleaned up the existing hole.
7. The seventh laser shot further cleaned up the existing hole.

2. First Derivative of PCB106B Pressure Sensor Output

The first derivative of the output from the PCB106B pressure sensor is shown in Figure 10. It is symmetrical against the horizontal axis, and the absolute value was consistently close to zero between the third shot (partial breakthrough) and the fourth shot (full breakthrough).

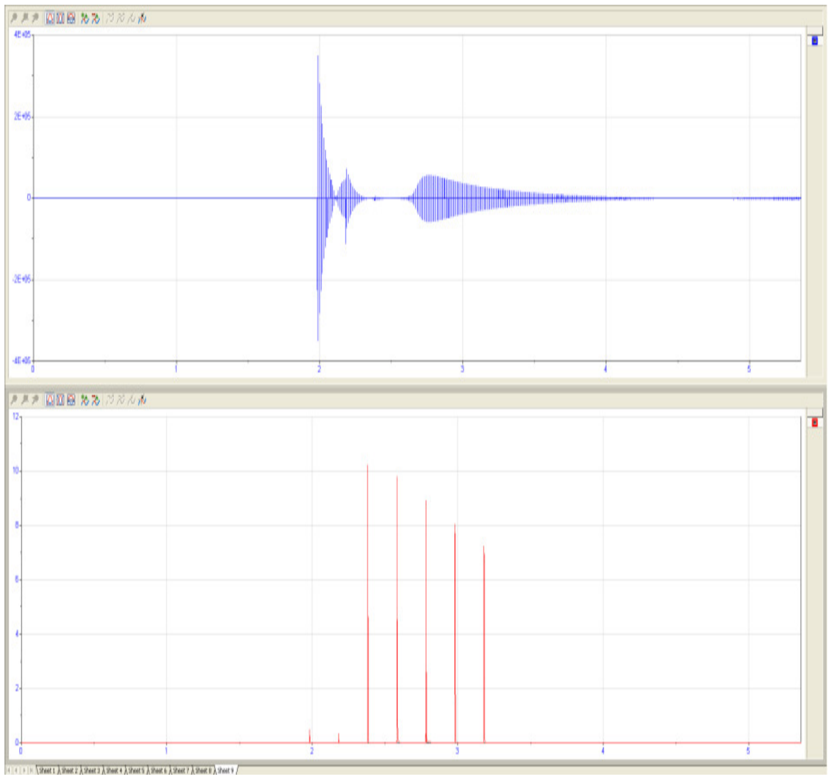


Figure 10. First Derivative (top) and Breakthrough Detector Output (bottom)
X Axis: Time in Second Y Axis: Sensor Outputs in Pa and Voltage

3. Second Derivative of Pressure Sensor Output

The second derivative of the output from the PCB106B pressure sensor is shown in Figure 11. After the distinct vertical line which represents the thermal contact between the laser beam and the sample, the sample temperature quickly changes, and the output of the second derivative was positive at the heating stage and negative at the cooling stage. Right after full breakthrough, the values of the second derivative gradually reached the continuous minimum value. Therefore, the moment of full breakthrough can be detected when the output of the second derivative becomes less than a certain minimum threshold value. At this point, the output of the breakthrough detection circuit turns off the laser to prevent subsequent back wall strike. The LabVIEW breakthrough detection program, which is shown in Figure 8, was implemented using this approach and is particularly useful when the conditions of the percussion laser drilling process are continuously changing. These conditions include the angle between the laser beam and the sample, the thickness of the sample, and the surface condition of the sample.

Because the sensor output is based only on amplitudes of thermal diffusion shock waves during the percussion laser drilling process, breakthrough detection is determined by the temperature conditions of the sample and is not affected by other factors.

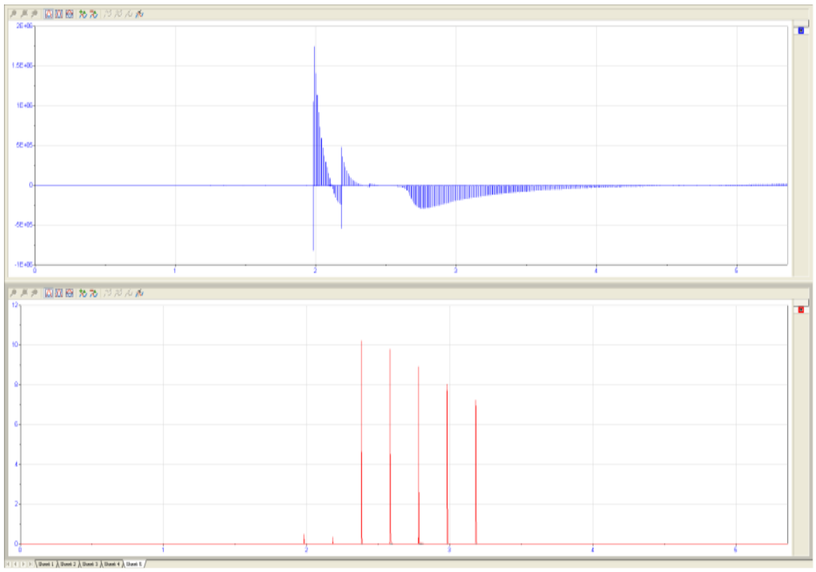


Figure 11. Second Derivative (top) and Breakthrough Detector Output (bottom)
X Axis: Time in Second Y Axis: Sensor Outputs in Pa and Voltage

Discussion

A. Overload Condition

The results of the experiments with laser-induced thermal diffusion shock waves are often mistaken to be the results of overload conditions. An overload condition occurs when the power supply of the sensor is not able to supply sufficient voltage to the sensor. When the PCB106B pressure sensor is used with the National Instruments PXI-4462 dynamic signal acquisition device, the power supply can provide up to 5 volts for the PCB106B pressure sensor. The power supply voltage consumption at the first shot in Figures 9 is calculated as follows:

Sensitivity of the PCB106B pressure sensor: 43.5 mV/kPa [2]
Maximum negative pressure in Figure 38: -81.099kPa
Maximum supply voltage required to operate the PCB106B sensor:
43.5 mV/kPa * 81.099kPa = 3,528mV = 3.528V

It is under 5 volts. Therefore, it is proved that the acquisition device supplied adequate voltage to the PCB106B pressure sensor.

An example of an overload condition is shown in Figure 12. The sampling rate was 100k samples/second, and the frequencies below 50KHz, which was the major frequency range of system gas noise, were included. The total number of laser shots was six, partial breakthrough occurred at the third shot, and full breakthrough occurred at the fourth shot. The power supply voltage consumption at the first shot in Figure 12 is calculated as follows:

Sensitivity of the PCB106B52 pressure sensor: 725mV/kPa [2]
Maximum negative pressure at the first laser shot in Figure 47: -13.316kPa
Maximum supply voltage required to operate the PCB106B52 sensor:
725 mV/kPa * 13.316kPa = 9,654mV = 9.654V

It is over 5 volts. Therefore, it is proved that the acquisition device did not supply adequate supply voltage to the PCB106B52 pressure sensor.

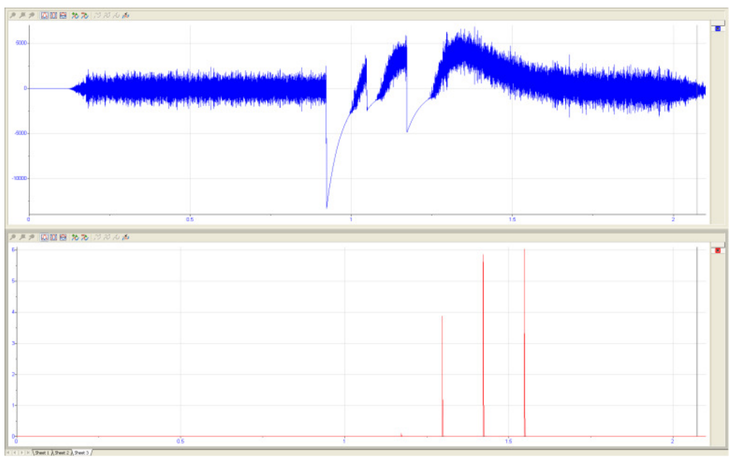


Figure 12. Overload Condition; PCB106B5 Pressure Sensor Output (top) and Breakthrough Detector Output (bottom)

B. Pressure Sensor versus Microphone

The PCBD20 ICP array microphone had been used from 2006. But it was damaged by high pressure caused by the percussion drilling process in the summer of 2007, and the PCB106B series pressure sensors were recommended by PCB engineers. So they have been used from the summer of 2007 to the present. In addition, PCB engineers decisively said that pressure caused by the percussion drilling process was beyond the microphone's measurement range and completely agreed that the pressure sensor was more appropriate than the microphone for breakthrough detection at CCAT. The system based on a microphone is inappropriate for the percussion drilling process because the maximum pressure reaches 81.099kPa at 1 inch from the sample. This pressure is 80 percent of the theoretical limit pressure of 101.325kPa at 1 atmosphere environmental pressure [6]. Even if the distance is increased twice to decrease the pressure to 20.275kPa, it is still over the allowable maximum pressure, 15.9kPa, of the PCB377A12 microphone, which has a sensitivity of 0.25mV/Pa [2]. The PCB377A12 microphone is one of the lowest sensitivity microphones made by PCB and is used in a high-pressure environment.

Even if the PCB377A12 microphone is used for breakthrough detection, it does not provide high sensitivity for laser-induced thermal diffusion shock waves as the PCB106B pressure sensor does. So the major advantages of the PCB106B pressure sensor over the microphone are high pressure resistance and high sensitivity for the laser-induced thermal diffusion shock waves. Therefore, the pressure sensor must be used in the laser percussion drilling process at CCAT to establish a consistently reliable control system that works under any conditions.

C. Cleanup Shots

After full breakthrough, the resolidified material might be left in the hole. A photograph of resolidified material is shown in Figure 13. The size of it can be estimated using the diameter of the calibration dots. In order to take out the resolidified material from the hole, cleanup shots are required after full breakthrough. But cleanup shots continuously drill the adjacent sample surface after full breakthrough, and we are in a dilemma as to whether to continue the laser shots or stop them. Therefore, the minimum amount of laser power that is required to take out the resolidified material from the hole is consumed for cleanup shots after full breakthrough. After cleanup shots, the laser must be immediately stopped to prevent damage to the adjacent sample surface.

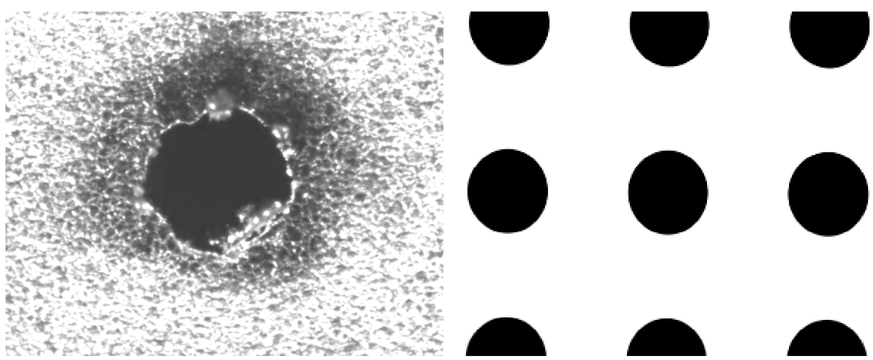


Figure 13. Resolidified Material and Calibration Dots (0.25mm Ø)

Conclusion

In the analog approach, the PCB106B pressure sensor output showed distinctive patterns before partial breakthrough, at partial breakthrough, at full breakthrough, and after full breakthrough, as shown in Figures 9, 10 and 11. Therefore, the system successfully detected the moments of breakthrough using the analog approach. Also, these results showed that this approach had unique advantages and disadvantages. For examples, test results showed distinctive patterns at partial breakthrough, at full breakthrough, and after full breakthrough. But they required complex algorithms to precisely analyze these patterns. Because all drilling conditions are constantly changing during actual fabrication of jet engine turbine blades, samples will be tested under many different conditions to establish a consistently reliable control system that works under any conditions.

Future Plan

The first fundamental experiments have been accomplished in a limited time period to prove that this method is feasible. The future objectives of this project are as follows:

Software Approach

Pattern Matching Algorithm
The PCB106B pressure sensor outputs distinctive patterns before partial breakthrough, at partial breakthrough, at full breakthrough, and after full breakthrough as shown in Figures 9, 10 and 11. In this project, the moment of breakthrough was determined using the threshold function of the LabVIEW breakthrough detection program shown in Figure 8. The moment of breakthrough can be also determined using the National Instruments pattern matching algorithm. Mr. Michael Callahan of the University of Illinois at Urbana-Champaign successfully controlled his patient's wheelchair using a similar approach in 2005. He interpreted his patient's nerve impulse signals as appropriate control signals for his wheelchair.

Hardware Approach

1. The angle between the laser and the sample
   Because the 20-degree laser shot is the standard for cooling hole drilling for jet engine turbine blades, this laser angle shot was used in this project. Varieties of angles will be tested to establish a consistently reliable control system that works under any angle conditions.

2. The thickness of the sample
   The thickness of the sample is significant because the 20-degree shot is the standard, and the laser beam has a long distance to penetrate under this angle condition. But the tested Waspalloy samples have a thickness of only 0.05 inches, and any thicker samples have not been tested in this graduate project. Therefore, thicker samples will be tested in the future.

3. The coating of the sample
   It is known that the thermal coating on the sample surface dramatically increases the sound signature. But coated samples have not been tested in this graduate project. Therefore, coated samples will also be tested in the future.

As mentioned above, this project requires a long time period to collect data to prove that this method works under any conditions, and I hope that this article will be the very first step for great success in the future.

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